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The New Toyota Inline 4 Cylinder 2.8L ESTEC GD Diesel Engine

Der neue Toyota 2.8L ESTEC GD Reihen-4-Zylinder-Dieselmotor

Abstract

Toyota has pioneered many environment-friendly technologies, notably its hybrid vehicles. Accordingly, the new 2.8L I4 ESTEC (Economy with Superior Thermal Efficient Combustion) 1GD diesel engine is being introduced into Toyota's diesel line-up as one of the attractive solutions for economy and reliability, especially in developing countries and for commercial vehicle markets.

In order to improve the engine thermal efficiency, significant modifications are implemented on fundamental structures compared to the previous model (3.0L 1KD engine) such as intake and exhaust ports layout, the valve system component and the DPF catalyst arrangement. As a result of these modifications, a down-sized turbo charger can be used. Moreover, fuel consumption is improved by 15%.

In addition, to meet Euro6 emission legislation, a urea SCR system is adopted (a Toyota first). As such, the exhaust system layouts were reduced to 3 types, decreased from 18 types in the previous model. This promotes engine installation flexibility for all the frame type vehicles.

Furthermore, the development efficiency was drastically improved by introducing "Combustion Design Methodology" (Toyota original concept), VDE (Virtual Diesel Engine/Toyota original simulation) and exhaust aftertreatment simulation.

Therefore, the GD engine achieves significantly silent combustion which is far superior to the conventional diesel engines and top level performance in fuel consumption, power output and exhaust emissions.

Kurzfassung

Bei der Einführung umweltfreundlicher Technologien nimmt Toyota eine Vorreiterposition ein wie z.B. bei den Hybridfahrzeugen. Entsprechend nimmt der neue 2.8L ESTEC GD Reihen-4-Zylinder-Dieselmotor in Toyota's Dieselportfolio eine Stellung ein als Aggregat für hohe Ansprüche an Ökonomie und Zuverlässigkeit, insbesondere in Schwellenländern und Nutzfahrzeugmärkten.

Um den thermischen Wirkungsgrad zu verbessern, sind signifikante Modifikationen in der fundamentalen Struktur des Vorgängermotors (3.0L 1KD) vorgenommen worden wie z.B. an Einlass- und Auslasskanälen, Ventiltrieb und Abgasnachbehandlungssystem. Diese Änderungen erlauben es, einen kleineren Turbolader zu verwenden. Insgesamt konnte der Kraftstoffverbrauch um etwa 15% verbessert werden.

Zudem wird ein Harnstoff-SCR-System erstmals bei Toyota angewendet, um die Euro6 Angasgesetzgebung zu erfüllen. Die Variantenzahl der Abgassysteme wurde von 18 (im Vorgängermodell) auf 3 reduziert. Dies erlaubt eine höhere Flexibilität für die Adaptierung des Motors für Modelle mit Rahmenstruktur.

Der Zeitaufwand für die Entwicklung konnte durch den intensiven Einsatz fortschrittlicher Methodik für Verbrennung ("Combustion Design Methodology", Toyota-internes Konzept), Gesamtmotor (VDE / Virtual Diesel Engine, Toyota-internes Konzept) und Abgasnachbehandlungssimulation drastisch reduziert werden.

Insgesamt erreicht der GD Motor eine herrausragende Stellung in Bezug auf leise Verbrennung, niedrigem Kraftstoffverbrauch, Leistungsentfaltung und Abgasemissionen.

1. Introduction

Toyota has developed a series of direct injection diesel engines with common rail injection systems in late 90s.This series includes passenger car engines (such as 1.4L ND and 2.2L AD) and commercial vehicle engines (such as 2.5L KD and 4.5L VD). These engines have been introduced worldwide and have met stringent emission legislations at the right time (Figure 1).

Due to their worldwide introduction, the diversified fuel trends were deeply investigated by both members of development and service divisions, and then a feasible timing of the common rail injection system introduction was decided. Today, these engines have been widely introduced into more than 140 countries in the world and have met various customers' needs specifically in reliability and fuel economy.

Toyota has strategically promoted environment-friendly technologies, especially its hybrid vehicles, in order to cope with the pressing environmental issues and has accordingly gotten some presence in many advanced countries. In contrast, clean diesel engines are enthusiastically supported in developing countries and/or in commercial vehicle markets because of their cost performance and powerful driving pleasure, that is, fuel consumption and low end torque. In response to the increasing competition in diesel markets, Toyota introduced the IMV (Innovative International Multi-Purpose Vehicle) consisting of pickup trucks, minivans and SUVs as global strategy vehicles for commercial vehicle markets in 2002 which have since gotten good reputation in various countries.

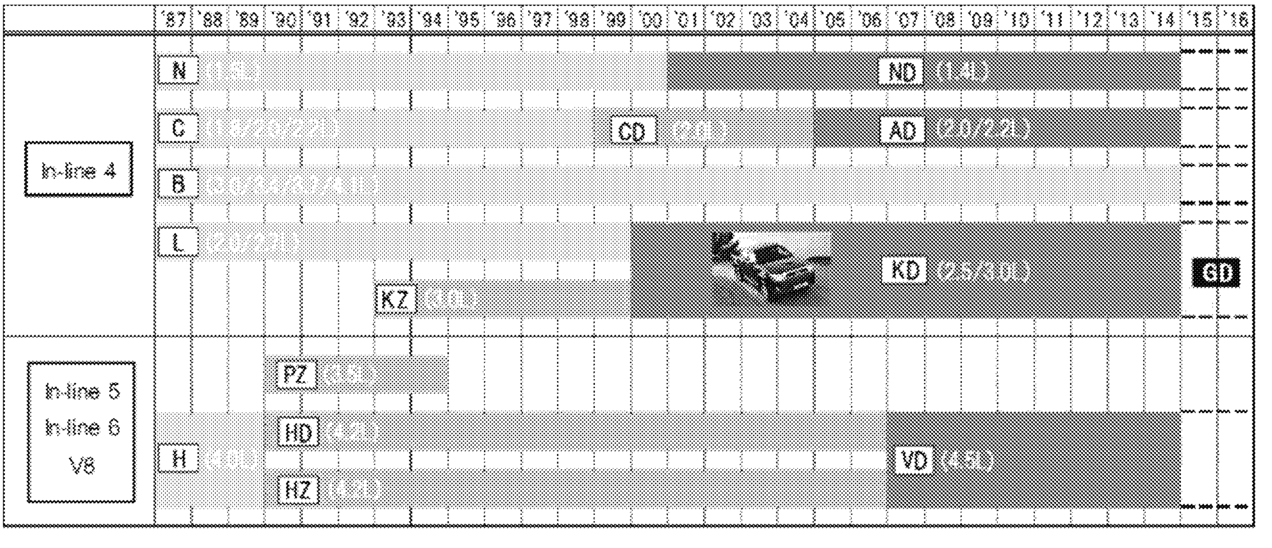


Figure1: The history of diesel engine in Toyota

In order to further respond to customers' requests and to comply with future stringent emissions legislation, Toyota decided to introduce a new ESTEC (Economy with Superior Thermal Efficient Combustion) GD engine instead of modifying the previous KD engine to thoroughly get better performance and quality.

Firstly, the new 1GD engine focused on the improvement of the basic parts function going back to the fundamentals, and also engine displacement was optimized considering future expansion of the line-up. Then finally, maximum thermal efficiency of 44% was achieved

which was top level in the world (Figure 2) and fuel consumption was also improved by 15% compared to the previous model. Moreover, the low end torque was also improved in spite of downsizing, while performing significantly silent combustion which is far superior to the conventional commercial diesel engines.
This paper will describe the system of the new 2.8L 1GD engine and its development process.

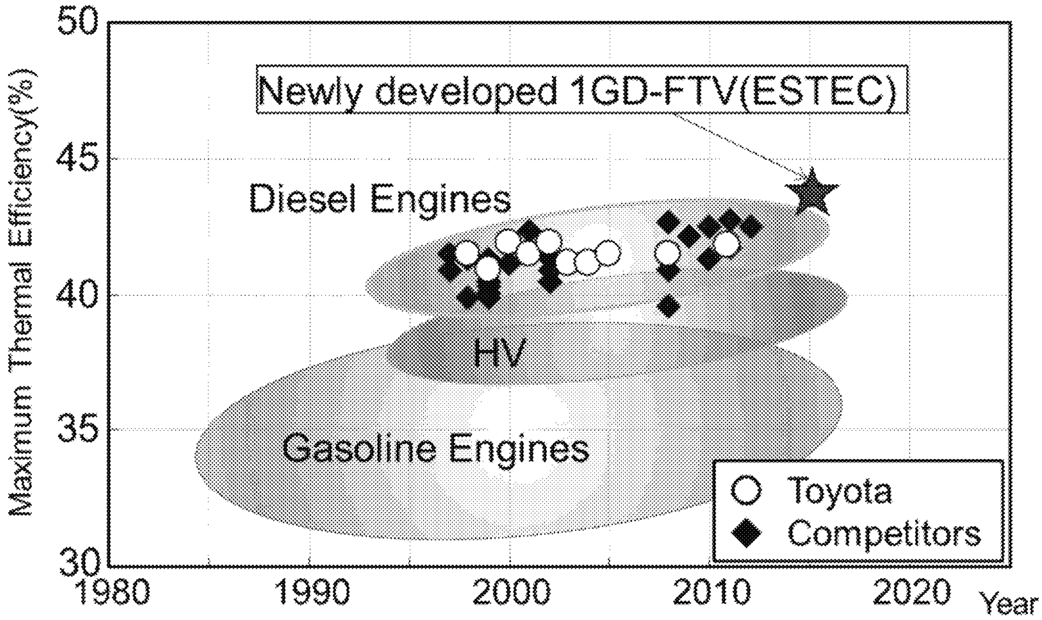


Figure 2: Maximum thermal efficiency

2. Specifications

Table 1 shows the main dimensions and specifications of the 1KD-FTV engine and the newly developed 1GD-FTV (ESTEC) engine for the Toyota IMV series.

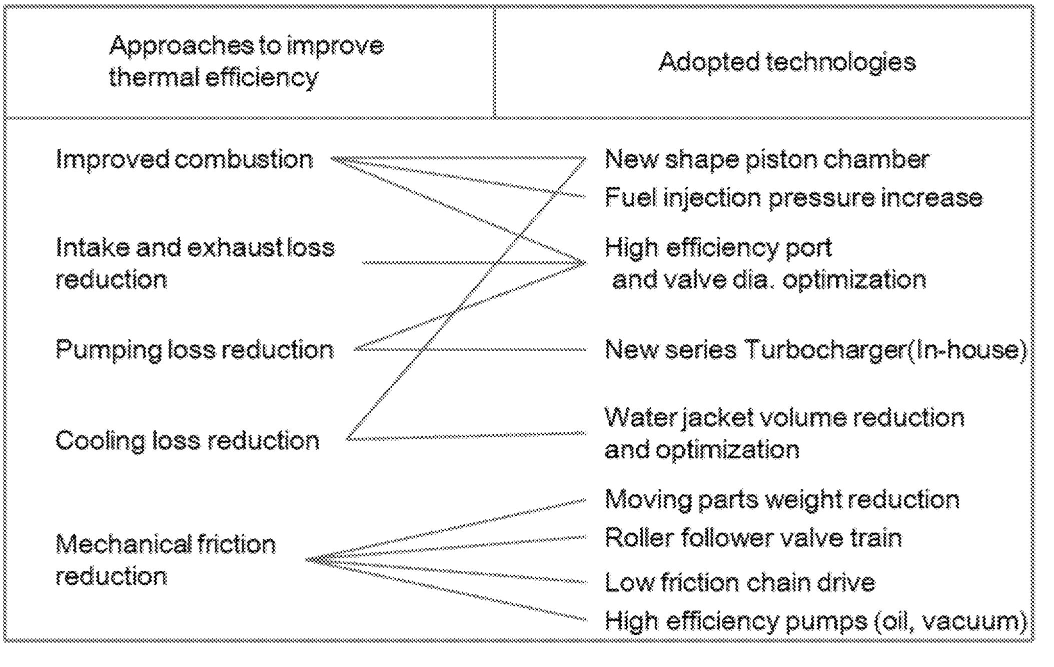
To improve the thermal efficiency, Toyota ESTEC engine adopted low cooling heat loss combustion. Generally, the diesel engine based on diffusion combustion with high swirl flow could have large heat loss through piston, cylinder head and bore. By optimizing port and piston chamber configuration, low flow type combustion which is not dependent on swirl and squish flow was achieved and it contributed to low fuel consumption [1]. Finally, 1GD engine achieved a maximum heat efficiency of 44% by reducing some kinds of losses like cooling heat loss, exhaust loss and mechanical loss.

Table 2 shows the technologies implemented to improve thermal efficiency and the following sections describe the major technologies.

Table 1: Specifications for Toyota ESTEC 1GD-FTV

Engine	1GD-FTV (ESTEC)	1KD-FTV (2014)
Engine Type	In-line4	←
Displacement [ml]	2755	2982
Bore x Stroke [mm]	Φ92 x 103.6	Φ96 x 103
Compression ratio	15.6	15
Fuel type	Diesel	←
Max. torque [Nm/rpm]	450/1600-2400	343/1400-3400
Max. power [kW/rpm]	130/3400	126/3600
Cylinder head/block	Al / FC	←
Valve system	DOHC, 4 valves per cylinder HLA+Roller rocker	DOHC, 4 valves per cylinder Direct
Fuel injection system	Solenoid(Max.2200bar)	Piezo(Max.2000bar)
Turbocharger	Single VNT D series	Single VNT C series
EGR system	HP hot and cooled EGR	←
Aftertreatment	DOC + DPF (engine side) + SCR (under floor)	DOC + DPF (under floor)
Emissions	Euro6	Euro5

Table 2: Technologies to improve thermal efficiency in GD engine



2.1 Low Swirl Cylinder Head

Generally, the combustion of a direct injection diesel has a close relationship with piston combustion chamber configuration, in-cylinder air flow and injection spray form. Accordingly, the requirement of intake airport has been changed with the remarkable recent progress of common rail injector technology. Previous 1KD engine applied double helical port to promote diffusive combustion with strong swirl, however the vortex by the helical port normally leads to pressure drop, generating a trade-off between pressure drop and quantity of air flow into the cylinder.

As such, the port figure was changed from double helical type to tangential and helical type as shown in Figure 3. In accordance with this design change, the configuration and number of head bolts were drastically changed.

Meanwhile, since the atomization of spray is promoted with a highly pressurized injection system to meet the stringent emission legislation, the strong swirl needed for conventional combustion was not required any more. In the new 1GD engine, development deeply focused on the reduction of the cooling heat loss in the combustion chamber. To enable low cooling heat loss combustion, swirl ratio was set to lower than the previous model (Figure 4) and at the same time exhaust port pressure loss was reduced by 43% (Figure 5).

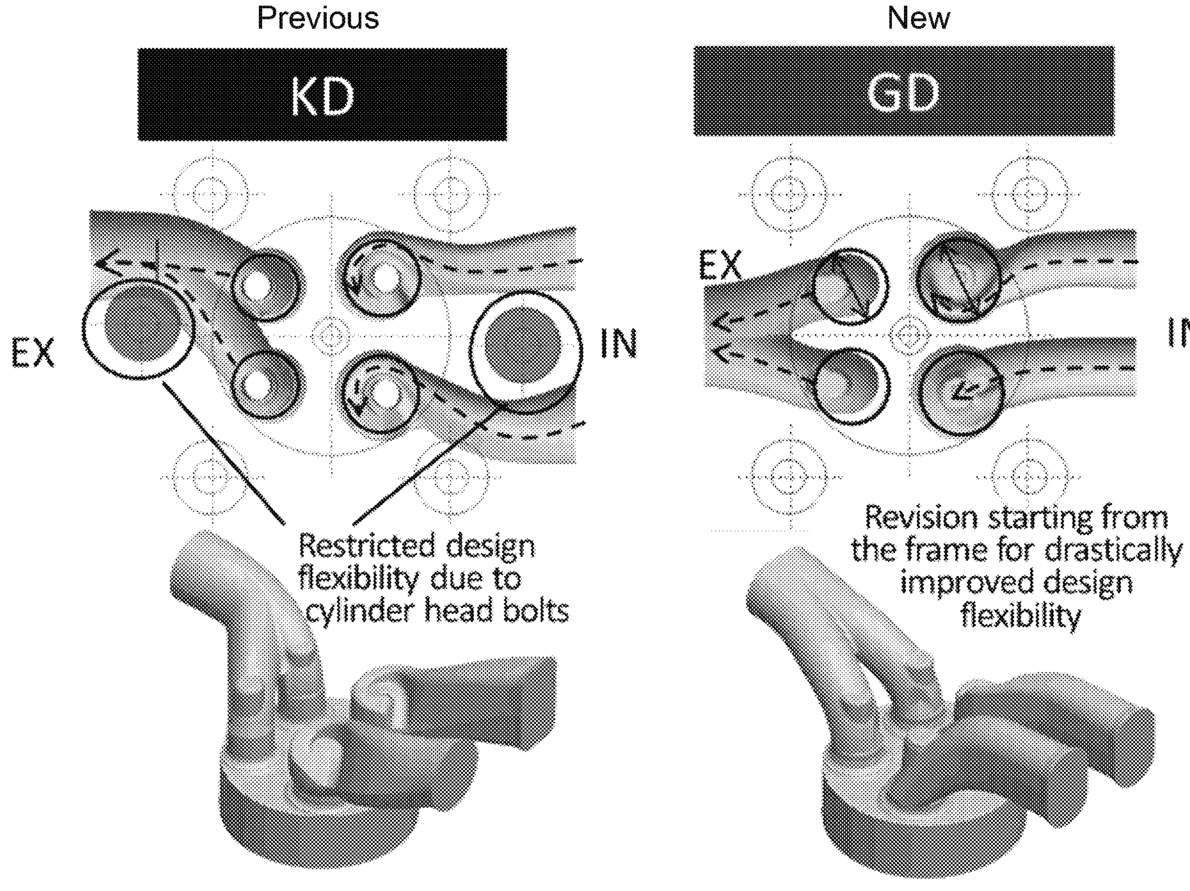


Figure 3: Comparison of port configuration

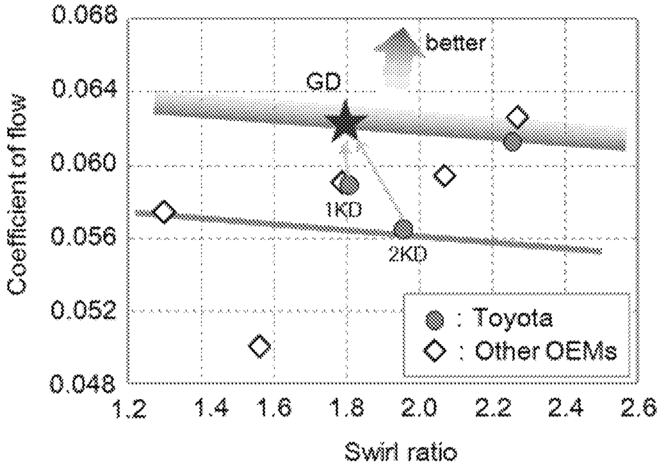


Figure 4: Swirl ratio and flow coefficient

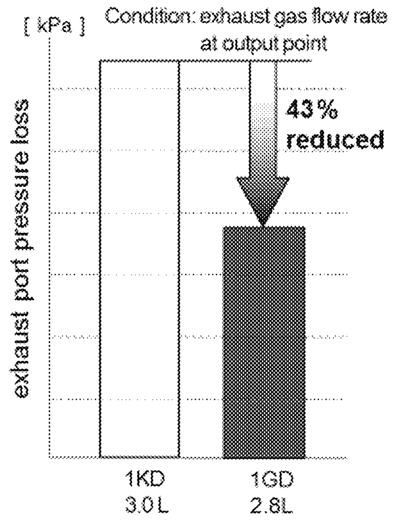


Figure 5: Comparison of exhaust port pressure loss (CFD)

2.2 Low Mechanical Friction Design

By analyzing, the friction loss of the previous 1KD engine, the utilization of the standard components of all Toyota diesel passenger cars was deeply investigated while considering reliability as the most important function.
The weight of reciprocating moving parts like the piston and connecting rod were drastically reduced. Specifically, the connecting rod was made from high-strength material, enabling quite low vibration which made it possible to eliminate the balance shaft. The front drive system was changed from gear and timing belt drive to a chain timing system with low friction spec. The valve system was changed from tappet direct hit type to HLA (Hydraulic Lash Adjuster) and roller rocker arm type. The oil pump was downsized and was designed with a shorter oil pipe line considering pressure loss. The vacuum pump was selected with high efficiency, small in size and low friction type.
As a result of all these technologies, engine friction was reduced by 28% compared to 1KD engine (Figure 6).

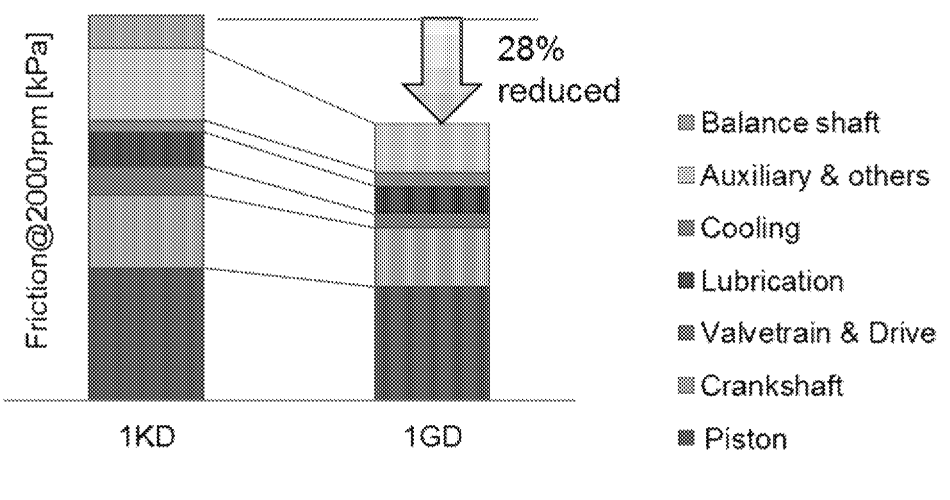


Figure 6: Comparison of friction losses

2.3 Injection System

To comply with future stringent emission legislation and for timely introductions in developing countries which have increasing demand for diesel engines year by year, it is necessary to realize not only high reliability but also silent combustion and low fuel consumption adequate for new generation engines. For this reason, the 1GD engine was introduced with the newest common rail injection system.

Firstly, the new system's high pressure pump achieves 2500bar of common rail pressure. The fuel quantity adjusting system was changed and fuel leakage from plunger sliding part was reduced.
In conventional suction quantity governing by using SCV (suction control valve), cavitation was generated by negative pressure from adjusting throttle and then the fuel was locally heated in the compressing process at plunger chamber which could accelerate fuel deterioration due to high pressure. As the new pump adopted the discharge adjusting by using PCV (pre-stroke control valve), negative pressure in the pump was not generated.
The leakage from plunger sliding part was reduced by securing the plunger sliding length and reducing the high pressure generation period by half because of single-cylinder. Thus pressure feed efficiency at 2500bar using the new system is higher than that of 2000bar using the conventional system (Figure 7).

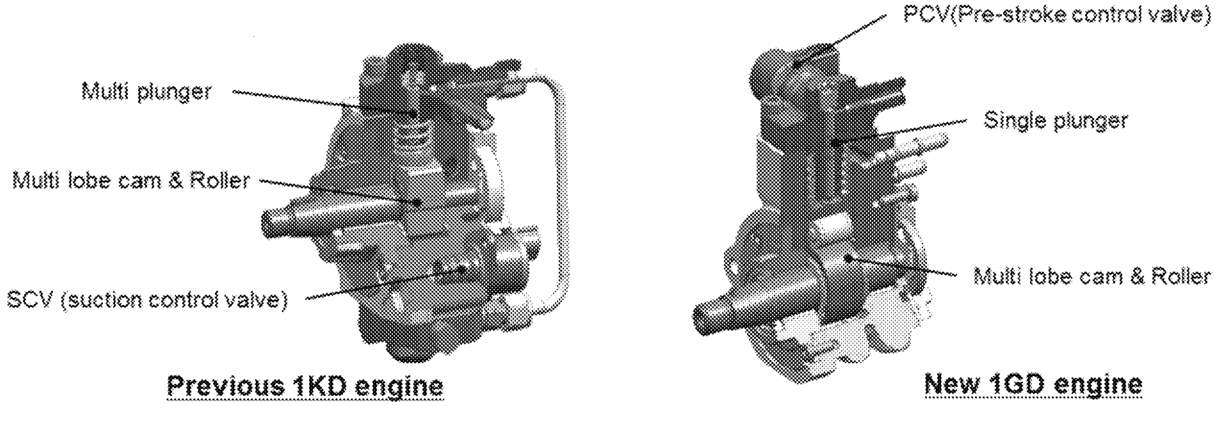


Figure 7: Super high pressure fuel pump

For the injectors, due to the requirement of extra high injection pressure, the pressure of the control chamber located in the upper portion of needle is controlled by the control valve and the injection is controlled by opening and closing of the nozzle needle using generated hydraulic force.

For the actuator driving control valve, solenoid was adopted because of the design potential of no lifetime limit and possibility of cost reduction by localized production around the world. Basically the driving force of a solenoid actuator is lower than that of piezo actuator which is designed for the higher function injector, thus 3-way-valve structure could not be adopted with the solenoid actuator. To overcome this weakness, a new control plate was introduced in the control chamber to control the needle valve opening/closing (Figure 8).

In addition to the adoption of the control plate, the new injector has no command piston to reduce fuel leakage and moving mass. In particular, increasing the injection pressure

raises the amount of fuel leakage and accelerates fuel deterioration. Reducing the clearance between sliding portions as a countermeasure could make durability worse against fine dust interference. Accordingly, reducing the clearance was a challenging issue for the high pressure line (Figure 9).
As mentioned above, by reducing the leakage to 1/10, the new injector achieved a maximum pressure of 2500bar that has never been reached [2].

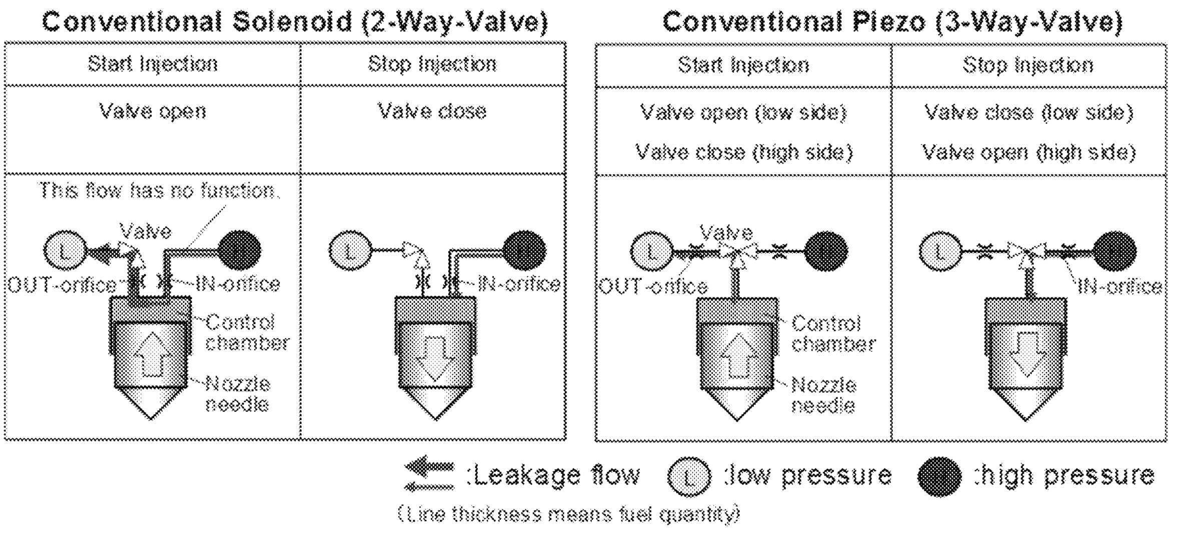


Figure 8: Concept of control valve and needle movement

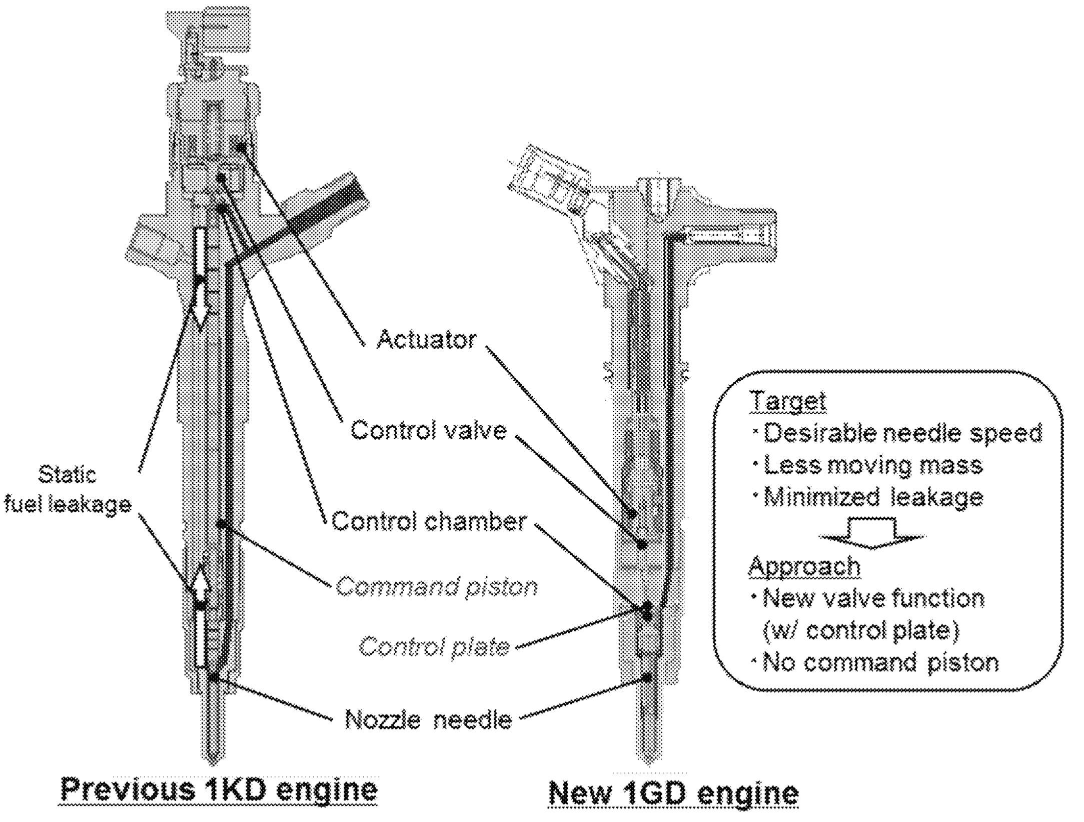


Figure 9: Concept of new injector

2.4 Variable Geometry Turbocharger

To comply with the exhaust emission legislation and to improve the product power such as fuel consumption and acceleration feeling, the turbocharger needs to be small in size, highly efficient and have a wide range usage. To satisfy this requirement, new D series variable geometry turbocharger was developed in-house (Figure 10). The bearing structure that is a fundamental structure of the turbocharger was modularized and contributes to reducing types of components.

Both high efficiency by the optimization of the compressor blade shape and improvement by entirely cutting forged metal provided high speed rotation. Thus, the turbocharger realized wide range usage. The turbine blade shape was optimized and adopted a full back disk type. The variable nozzle vane mechanism was designed as a structure that is not influenced by thermal deformation of turbine housing, and the vane clearance was reduced by supporting vane at both ends. For these reasons, the efficiency was highly enhanced over all engine operation area. The bearing structure selected was semi float type with the optimization based on oil film theory. Thus, vibration was reduced by half compared to the previous model. As mentioned above, the new turbocharger realized both high efficiency and wide range usage, even though it was designed smaller in size than the previous model (Figure 11). Additionally, the turbocharger contributed to the dramatic improvement in fuel consumption and transient response (Figure 12).

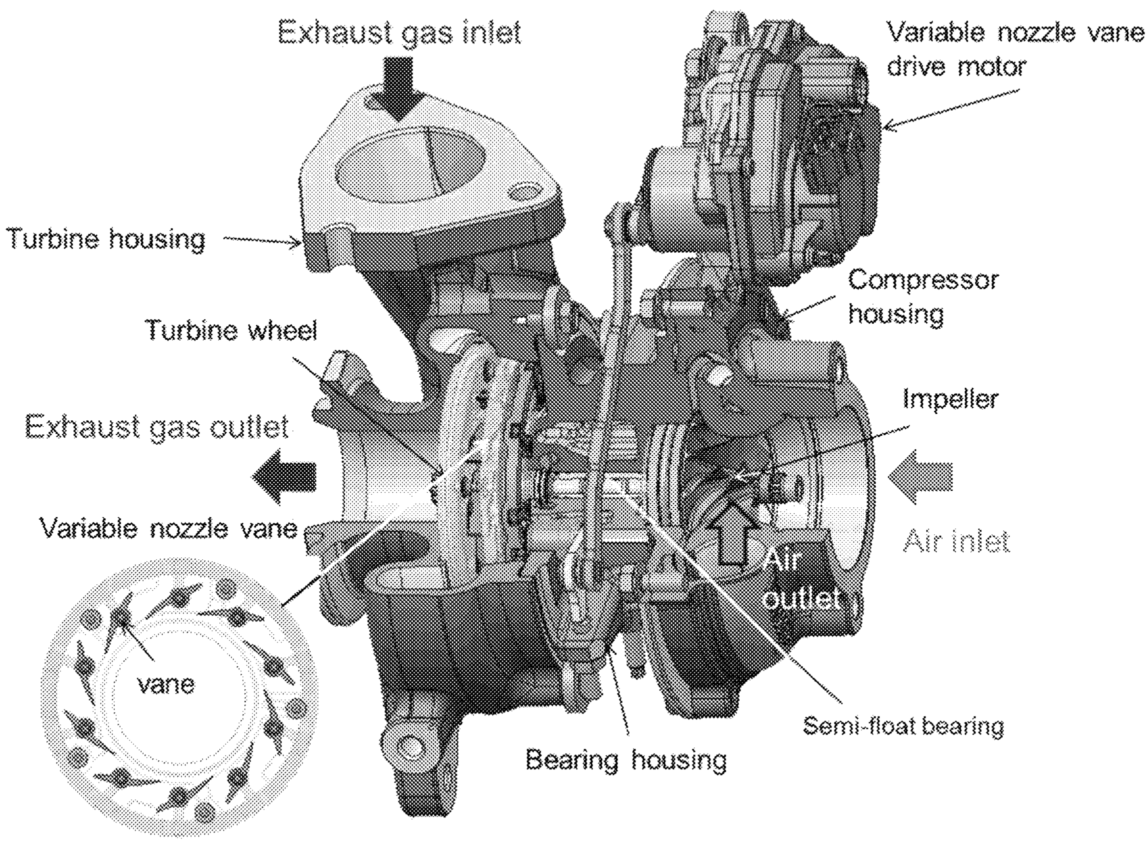


Figure 10: Variable Geometry Turbocharger (CT8DV)

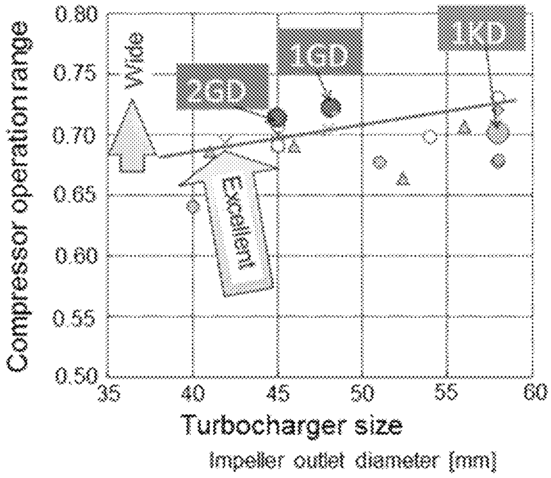


Figure 11: Compressor operation range

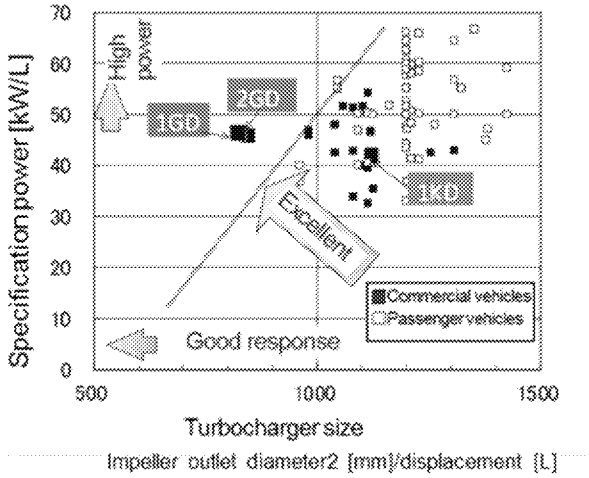


Figure 12: Specification power

2.5 Modular Exhaust System

To cope with the combination of vehicle and emission legislation, the exhaust system layout variations increased in the conventional engine development process. To solve the difficulty of new engine installation, DOC/DPF could be inserted or removed according to emission legislation. Therefore, the exhaust system layouts were integrated to 3 types from 18 types in the previous model.
This communization provided significantly efficient development and cost reduction. Figure13 shows the example of modular design. Only the DOC was laid horizontally adjacent to engine for Euro 3 and Euro 4 variations, while the DOC/DPF was laid horizontally adjacent to engine for Euro 5 variation.

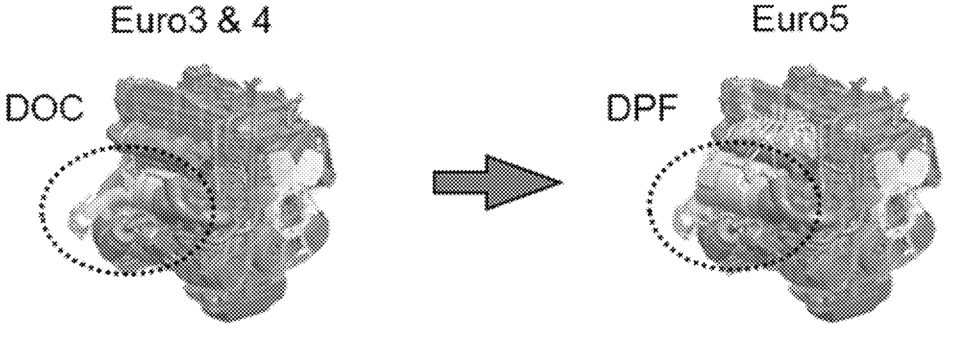


Figure 13: Modular design concept

In addition to the modular design, the Euro 6 variation adds an underfloor urea SCR system compared to the Euro 5 variation without changing engine design (Figure 14). The urea SCR was arranged underfloor of the vehicle and it was communized as well. To unify the layout from the end of DPF to the SCR catalyst, only one type of the urea SCR system was designed. This significantly contributed to the efficient development.

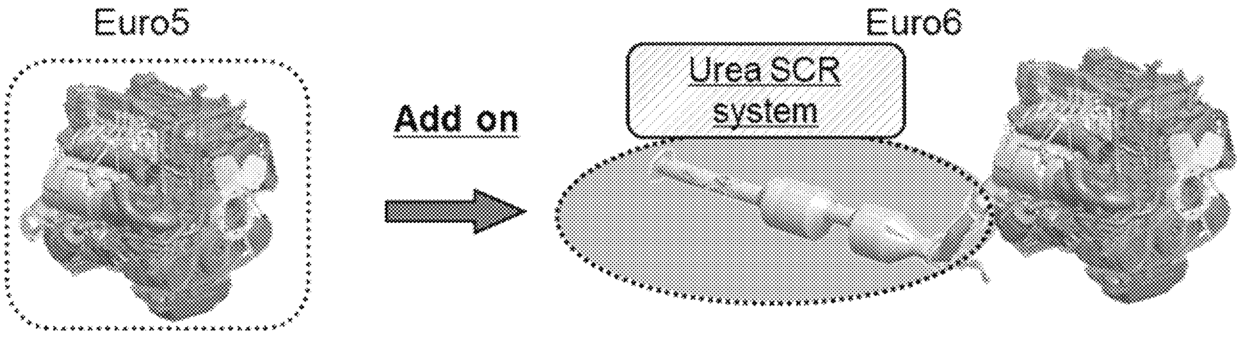


Figure 14: Euro6 SCR system based on Euro5 DPF system

2.6 Urea SCR System

To meet Euro 6 emission legislation, there are three system line-ups for NOx aftertreatment system. Toyota considered the NSR for small passenger cars, DiAir (Diesel NOx aftertreatment by Adsorbed Intermediate Reductants) for medium passenger cars [3] [4] and SCR for large passenger cars and commercial vehicles (Figure 15). From this viewpoint, GD engine uses the urea SCR system whose adoption is a first for Toyota [5].

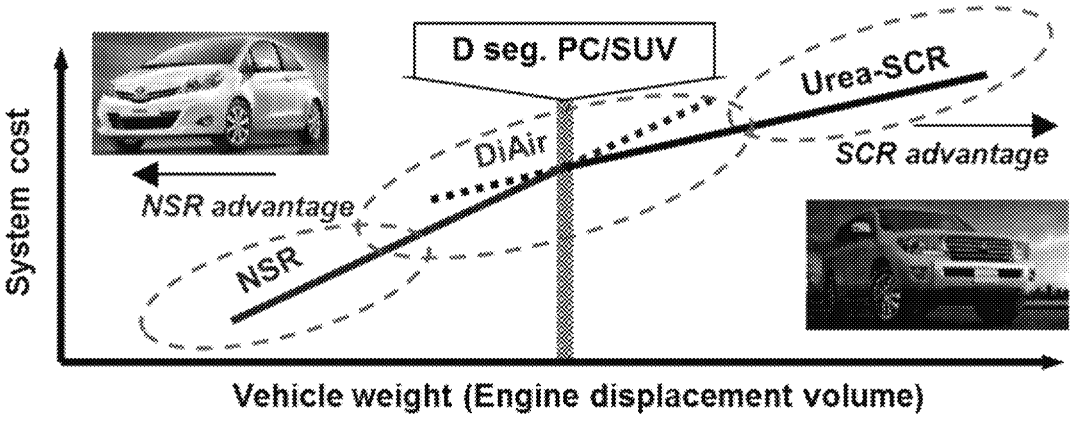


Figure 15: Cover range of each NOx aftertreatment system

Warm-up performance of the urea SCR catalyst is important to increase NOx conversion efficiency. In this development, SCR catalyst and diffuser plate were arranged close to engine (Figure 16). For this reason, SCR catalyst was warmed up rapidly and contributed to low emissions and fuel consumption. This arrangement leads to a short distance for urea dispersion, and deterioration of dispersibility becomes a concern. To resolve this, the configuration of exhaust pipe and mixer was optimized by using CFD. Thus, urea was dispersed uniformly regardless of operating condition (Figure 17).

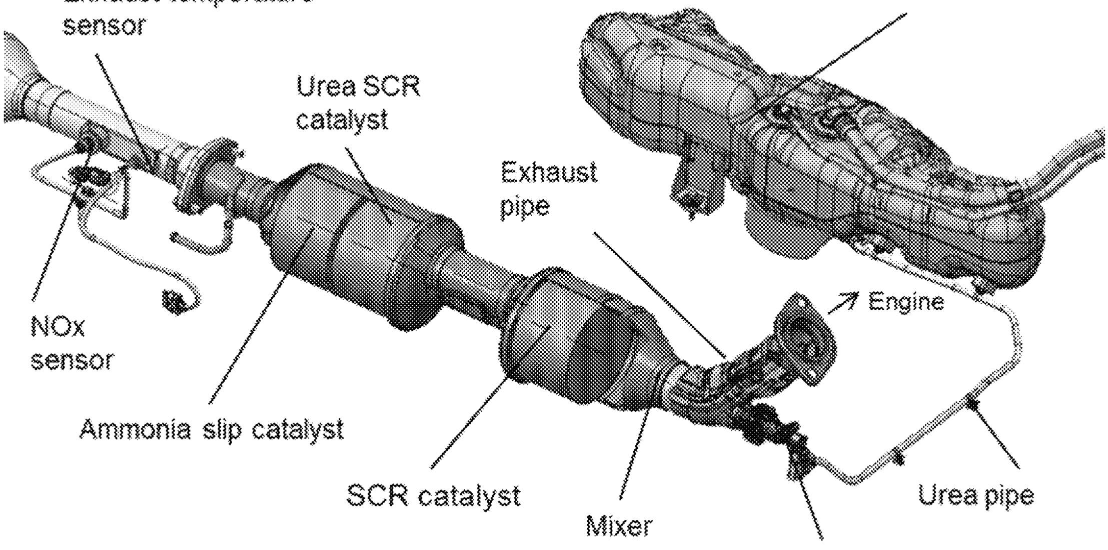


Figure 16: Aftertreatment system for Euro 6

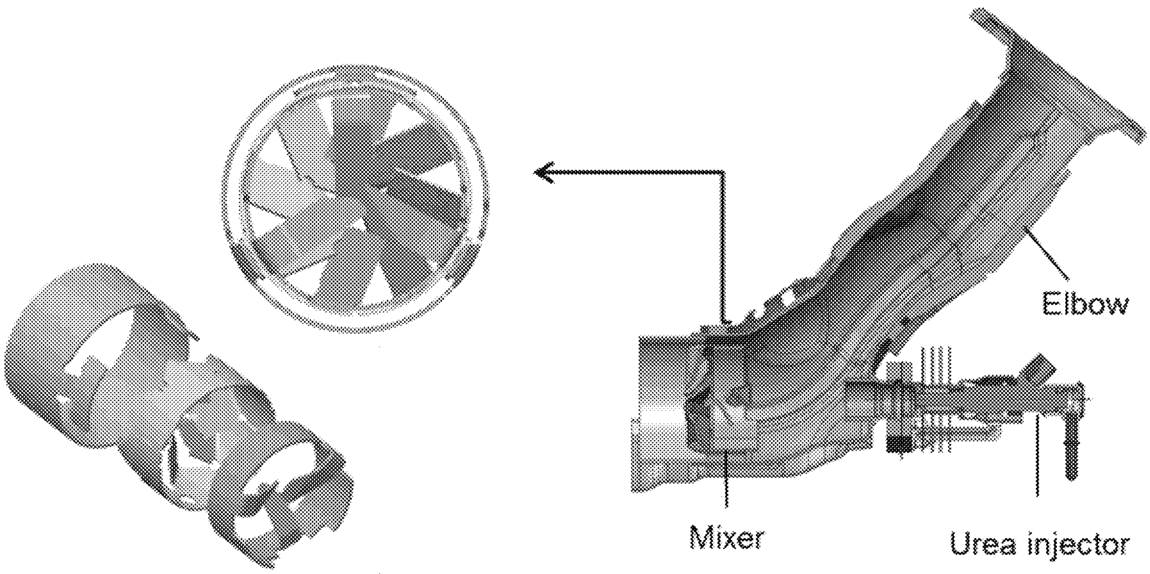


Figure 17: Urea injection system

Various engine control models were introduced for SCR system. They contributed to efficient calibration, accuracy improvement and cost reduction. In this paper, two of the control models are described.
The engine out NOx model estimates the mass of NOx flowing into the SCR catalyst based on engine operation condition and intake oxygen concentration which has a high correlational relationship with NOx without sensing the engine out NOx directly. The estimated value is used for the calculation of amount of the urea (Figure 18). The adoption of this model led to the elimination of a NOx sensor and system cost reduction.

Likewise, the SCR inlet temperature model estimates the temperature based on the temperature sensor value of DPF out without direct sensing. During estimation, the corrected value using flow rate of exhaust gas and influence of heat transfer was considered. The estimated value was used for the judgment of start/stop of urea injection or correcting the amount of urea. The adoption of this model enables the elimination of a SCR catalyst inlet temperature sensor.

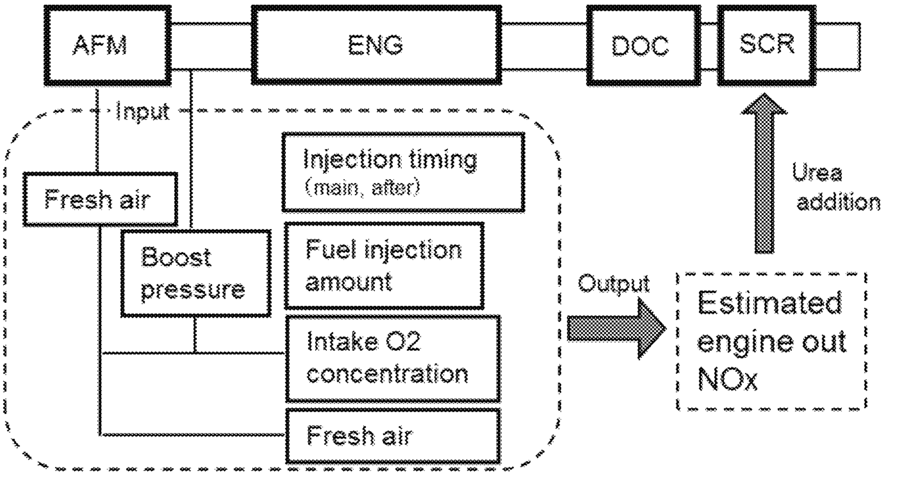


Figure 18: Schematic of NOx estimation model

By maximally utilized high NOx conversion efficiency of the urea SCR system, fuel consumption was improved by 3% compared to the Euro 5 system. The Euro 5 system without NOx aftertreatment system must maintain constant turbine back pressure to ensure necessary EGR ratio by controlling Variable Geometry turbocharger. In contrast, the Euro 6 system depends on the SCR catalyst to reduce NOx, for this reason, the back pressure could be reduced to the minimum and then the system could have higher potential to reduce fuel consumption and meet emission legislation at the same time.

As mentioned above, the Euro 6 system can be easily established by adding the SCR system to the Euro 5 system with small calibration change. Furthermore, fuel consumption could be simultaneously improved. However, since the SCR system relies on the urea supply by users, it is necessary to optimize the entire urea system and keep urea maintenance pitch longer than that of vehicle maintenance for users' convenience.

3. Model Based Design

Combustion Design Methodology

It is also important to remember that V process based on MBD was introduced as the key approach throughout the development (Figure 19). In the previous process, too much man-hours were spent on the PDCA cycle of try-and-error type, namely trial production → evaluation → investigation of problem → modification of design. In that process, to optimize performance and fuel consumption for example, the operating values like fuel injection quantity and fuel injection timing were directly calibrated.

In contrast, with the V process applied this time, “Combustion Design” (Toyota original concept) process was implemented on the highest order process of the left bank (system design process) and “Physical State Index” was introduced as the calibration target.

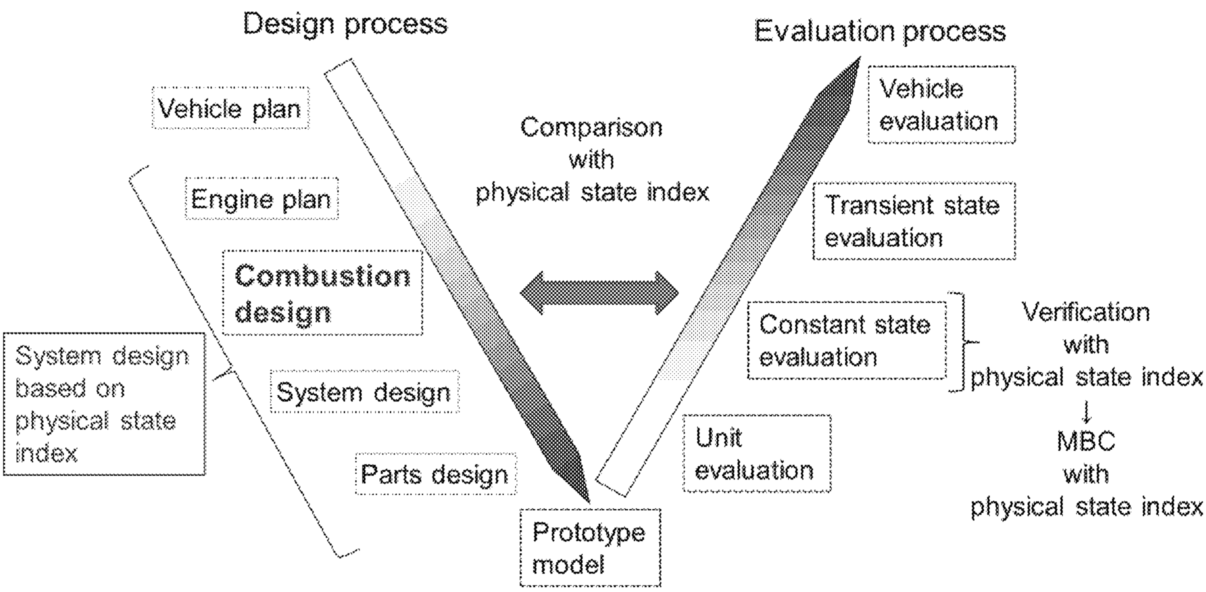


Figure 19: Engine development V process

Firstly, “Combustion Design” means the calculation for the necessary physical state index to achieve “Ideal Combustion” considering the requirement performance like emissions, engine output power and combustion noise.
There are two types of physical state index, one is “the physical state index of the exhaust gas system” to meet emission legislation like NOx and smoke, and the other one is “the physical state index of the fuel injection system” to achieve the target performance like fuel consumption, combustion noise and anti-misfire.

For a physical state index of exhaust gas system, intake oxygen concentration was applied as a NOx control factor and air fuel ratio was applied as a smoke control factor. Based on the previous engine database, each target physical state index was converted into the required operation value like EGR ratio or boost pressure (Figure 20).

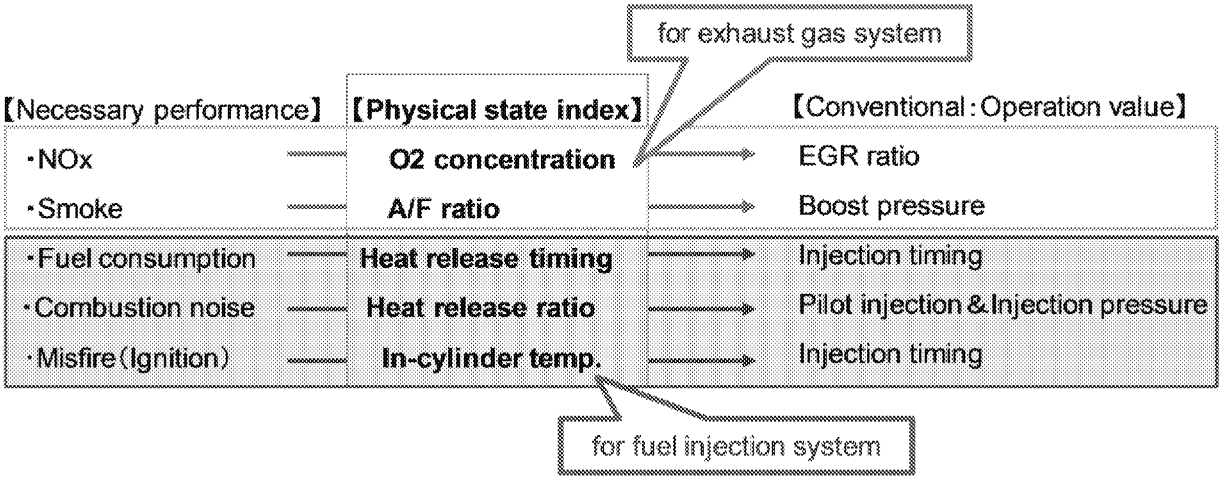


Figure 20: Physical state index

Finally, the required operation values were mapped and validated until necessary physical state index was achieved by using the tool called VDE (Virtual Diesel Engine : Figure 21). This tool can also estimate temperature and pressure of several parts at the same time. It could be also utilized for basic function component design like EGR cooler or turbocharger as well.

In contrast, for a physical state index of fuel injection system, heat release timing was applied as a fuel consumption control factor and heat release rate was applied as a combustion noise control factor. These were converted into required operation value like injection timing or pilot injection (or injection pressure) as well by combustion simulation tool called UniDES (Universal Diesel Engine Simulator) in VDE [6]. This tool can calculate the penetration of pilot injection atomization, spray interference, cylinder temperature and heat release ratio, then combustion analysis can be fully performed with high accuracy considering heat loss.

Secondly, on the evaluation process, simulation results from design process were verified by MBC (Model Based Calibration) to enhance efficiency. Firstly, the statistical engine model was created by implementing the global MBC on the actual engine dyno. This model can be used for the verification between required physical state index versus actuator operating values and actual engine outputs versus physical state index. Thus these results can provide us the root cause of the gap between estimation and experiment, whether it could be the matter of calibration quality or hardware design itself.
As a result, man-hours of the design process were also reduced by 40% compared to the previous process.

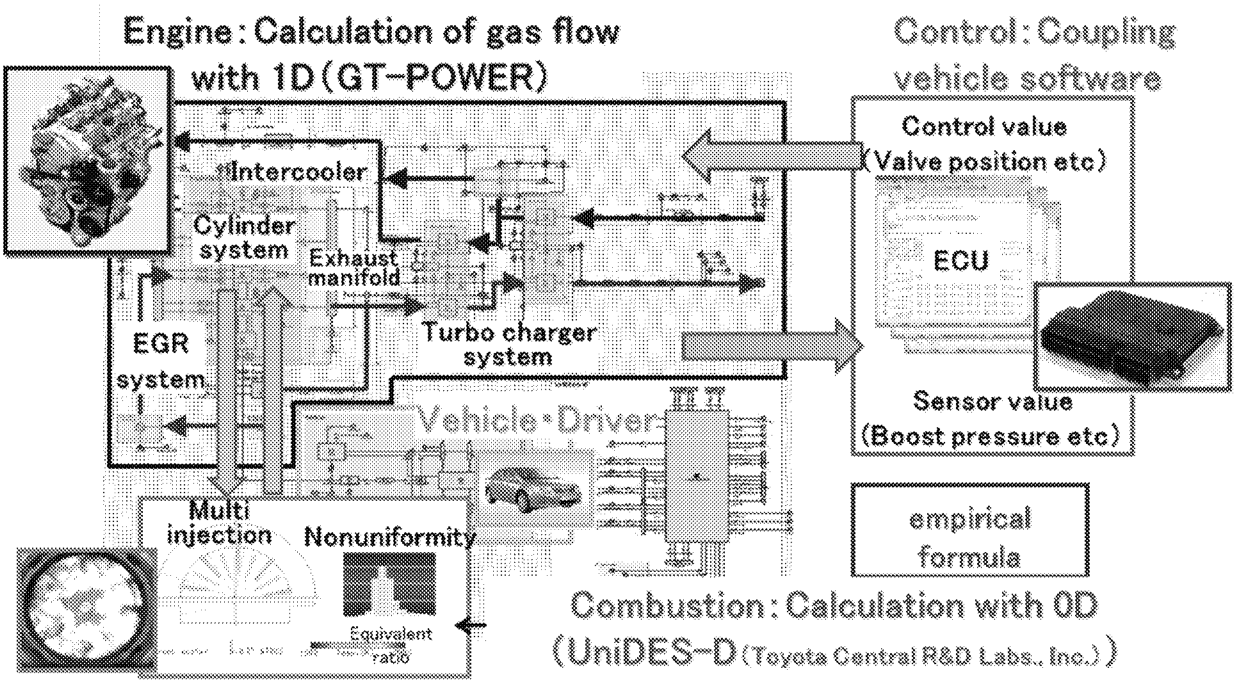


Figure 21: Virtual Diesel Engine (VDE)

4. Engine Performance

4.1 Power Output and Torque

The new GD engine was 8% downsized compared to the previous 1KD engine. Furthermore, low end torque was improved by 11% and maximum torque was also improved by 25% through introducing a new small high-efficiency variable geometry turbocharger, then the low and middle torque which is quite important for commercial vehicles in dynamic performance was significantly improved. Maximum output power was improved by 3% (Figure 22).

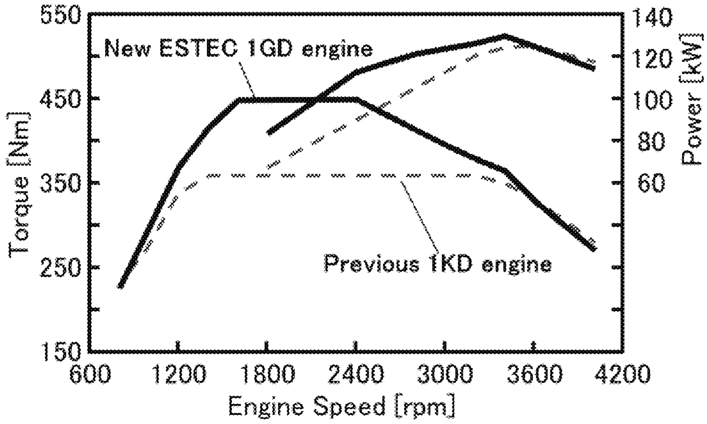


Figure 22: Power output and torque curves

4.2 Emission and Fuel Consumption

Reducing friction for each component parts, improving intake/exhaust port performance, optimizing combustion chamber configuration, introducing the new turbocharger and the new injector, reducing pressure loss for intake/exhaust system (like as EGR system) and optimizing the cooling system (e.g. the amount of engine cooling water, engine cooling portion), the maximum thermal efficiency achieved is 44% which is top level in its class (Figure 23). Specific fuel consumption ratio achieved is 200 g/kW.h in the wide range and fuel consumption of NEDC mode was also improved by 15% compared to the previous model (Figure 24).

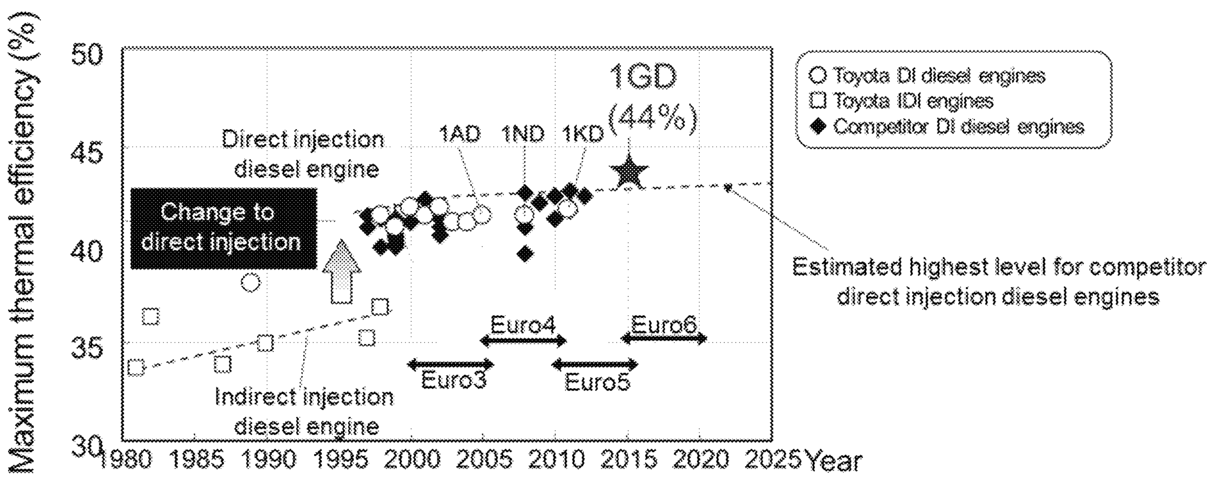


Figure 23: History of maximum thermal efficiency

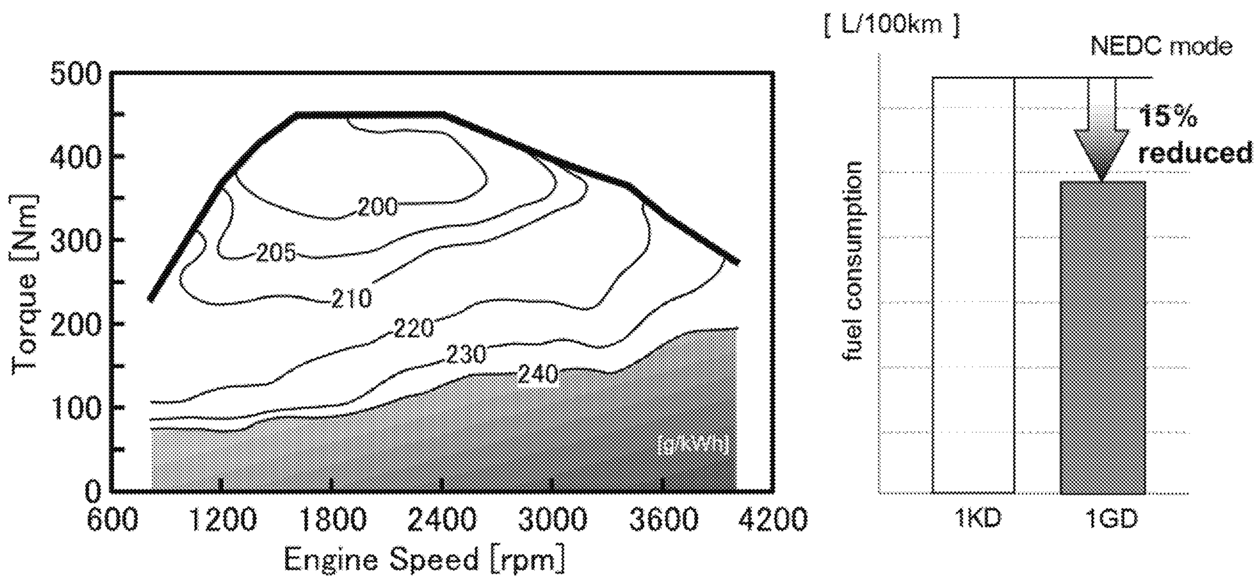


Figure 24: BSFC map and fuel consumption

4.3 Acoustics (NV)

For minimizing combustion noise, besides generally damping structure improvement method, MBD was also applied for the combustion noise design process.
The low and middle speed torque was significantly improved, while combustion noise level was reduced by 2-5 dB compared to the previous model as shown in Figure 25.
Additionally start timing of main injection and inclination of heat release ratio were kept constant in all engine operation area, therefore the noise of high-frequency band, namely diesel noise was extraordinarily reduced (Figure 26, 27 and 28).

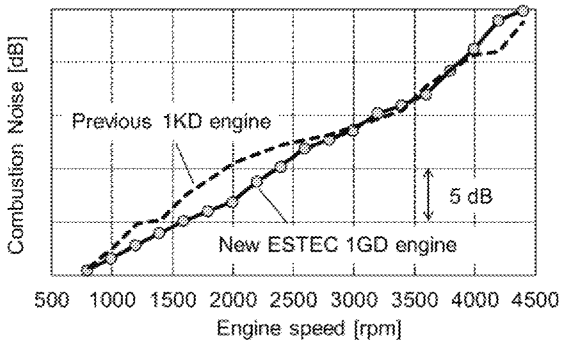


Figure 25: Combustion noise

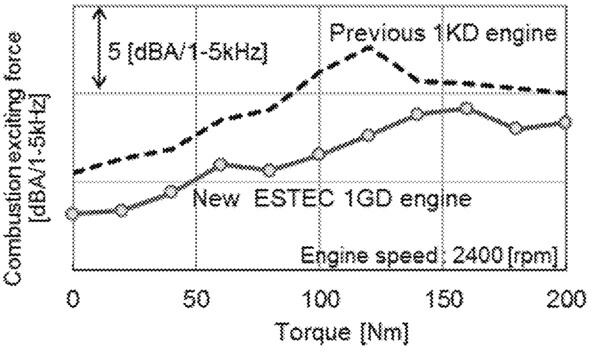


Figure 26: Combustion exciting force

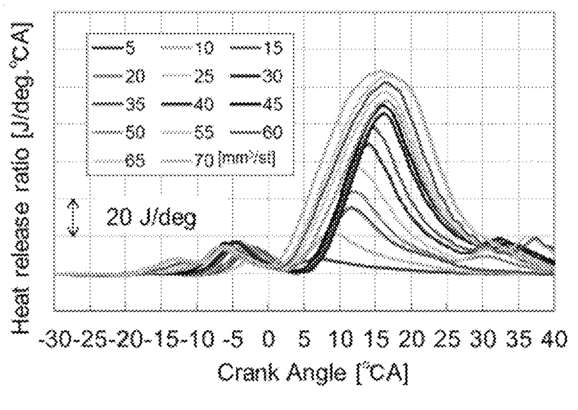


Figure 27: Heat release ratio

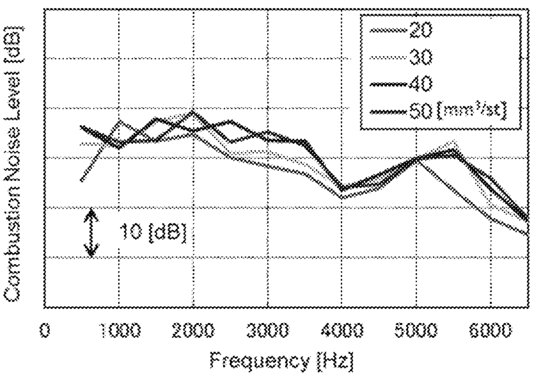


Figure 28: Combustion noise level

5. Conclusion

The new Toyota ESTEC 2.8L GD engine achieved the following results by fundamental structure change, introducing modular concept for the aftertreatment system and implementation of MBD process.

1) Drastic reduction of moving parts weight, the best selection of friction items and performing low cooling heat loss combustion enabled the maximum heat efficiency of 44% which is top level in the world.

2) Introducing modular concept for the aftertreatment system could introduce a plug-in design for the DOC/DPF/SCR systems, therefore the exhaust system layouts were communized to 3 types from 18 types of the previous model. It also enabled efficient development and extreme cost reduction.

3) Implementing V development process based on MBD drastically reduced redesign or recalibration and man-hours of the design process were reduced by 40% compared to conventional process.

4) Introducing "Combustion Design" concept made the required function clear to realize target physical state index and therefore optimization of engine components got easier by introducing VDE. As such, extremely silent diesel combustion was achieved.

6. References

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